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Mars Exploration Rover Transverse Impulse Rocket Cover Thermal Protection System Design Verification

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Arc jet test results are summarized of the Mars Exploration Rover silicone-impregnated reusable ceramic ablator (SIRCA) transverse impulse rocket system (TIRS) cover test series in the Panel Test Facility at NASA Ames Research Center. The primary objective of this arc jet test series was to evaluate design details of the SIRCA TIRS cover interface to the aeroshell under simulated atmospheric entry heating conditions. Four test articles were tested in an arc jet environment with three different seal configurations. The test condition was designed to match the predicted peak flight heat load at the gap region between the SIRCA and the backshell and resulted in an overtest for the apex region of the SIRCA TIRS cover. Repeatable thermocouple data were obtained and compared with SIRCA thermal response analyses. The one-dimensional thermal response prediction compared well with the thermocouple data for the location at the backshell interface. For the apex region of the SIRCA TIRS cover, a one-dimensional thermal response analysis resulted in an overprediction because there were strong multidimensional conduction effects due to the TIRS cover geometry. In general, the test results provide strong experimental evidence that supports the adequacy of the baseline seal design.

Introduction

THIS report details the results of a test series in a simulated entry environment for a new design on the Mars Exploration Rover (MER) spacecraft. The MER mission is slated to land two large scientific rovers on the surface of Mars. MER-A and MER-B launched successfully on 10 June 2003 and 7 July 2003, respectively. The goal of the identical rovers is to learn about ancient water and climate on Mars. The entry, descent, and landing of the rovers will duplicate the Mars Pathfinder (MPF) mission. The thermal protection systems (TPS) on the two spacecraft, shown in Fig. 1, will use identical materials to those used on MPF. MPF used the NASA Ames Research Center (ARC)-invented TPS material silicone impregnated reusable ceramic ablator (SIRCA-15F) on the backshell interface plate (BIP) due to the material's excellent ablative and insulative properties. In addition, SIRCA offered ease of machinability to any shape and versatility in integrating numerous penetration hardware required on the BIP because the BIP is the interface to the cruise stage. The nomenclature of SIRCA-15F refers to SIRCA manufactured from 0.19-g/cm^3 (12-lb/ft^3) bulk density fibrous refractory ceramic insulation (FRCI-12), with a final SIRCA bulk density of 0.264 ± 0.024 g/cm^3 (16.5 ± 1.5 lb/ft^3).

For the MER spacecraft, NASA ARC manufactured the SIRCA material for use on the BIP, just as was done for MPF. In addition, NASA ARC manufactured SIRCA material for thermal protection of the transverse impulse rocket system (TIRS) covers. The TIRS is a new feature that was not required for MPF. Its purpose is to minimize the total self-induced horizontal velocity at impact such that it meets the airbag system impact velocity requirements. Three TIRS rocket nozzles are spaced around the backshell at 120-deg intervals, as shown in Fig. 2a. Because the TIRS rocket nozzles extend outside of the backshell (shown in Fig. 2b), a dome cover with TPS is required to protect the nozzles during atmospheric entry (shown in Fig. 2c).

SIRCA was baselined as the TPS for the TIRS cover primarily due to its ease of machinability and interface to the backshell TPS, SLA-561S, a Lockheed Martin Astronautics (LMA) TPS material. The TIRS cover structure is a T300 composite structure, and the SIRCA TPS is machined to match the cover outer-mold-line dimensions and then bonded to the composite structure with a silicone adhesive. A titanium bracket is fastened to the backshell structure and the TIRS cover is fastened to the bracket, as shown in Fig. 3. The titanium fasteners for the TIRS cover are exposed to the flow, although they are recessed from the surrounding SIRCA surface. The baseline seal design consists of a Nextel™ rope placed around the entire perimeter of the gap at the bracket and aeroshell interface and then sealed with a silicone adhesive.

Because MPF was the first flight application of SIRCA, an extensive arcjet test series was conducted in 1995 to evaluate SIRCA-15F for use on the MPF BIP. To verify the flight-lot SIRCA-15F material under aerothermodynamic heating conditions representative of the MER trajectory, an arcjet test series was performed in September 2001 to obtain ablation and thermal response data for SIRCA-15F and to evaluate interfaces to various BIP hardware penetrations.[1] The MER SIRCA-15F BIP arcjet test series concluded that SIRCA material thermal response predictions were consistently 2–10% higher than the thermocouple data, thus verifying an accurate and conservative SIRCA-15F material thermal response model. This thermal response model was used by NASA ARC to determine the required thickness of SIRCA-15F to provide thermal insulation to the TIRS cover, based on Jet Propulsion Laboratory (JPL)-provided design requirements.[2] Although the SIRCA-15F thermal response model conservatism was verified through a separate arcjet test series, an additional TIRS cover arcjet test series was recommended by NASA ARC to evaluate specific design details of the SIRCA

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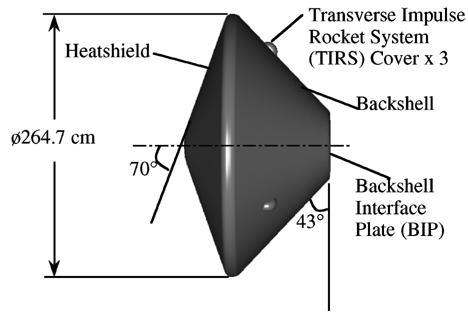


Fig. 1 MER spacecraft geometry.

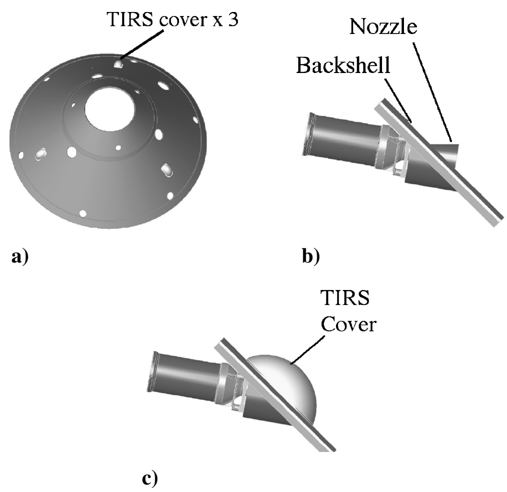


Fig. 2 TIRS: a) isometric view of MER backshell and three TIRS locations, b) side view of TIRS extending outside of backshell, and c) TIRS cover attached to backshell (courtesy of JPL).

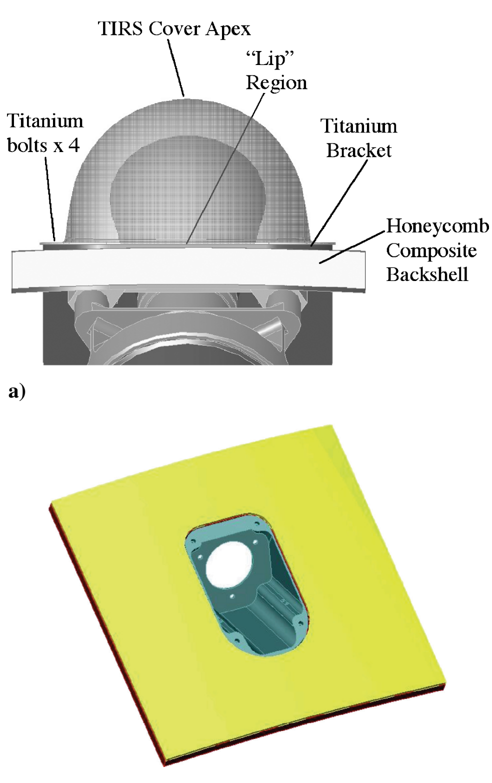


Fig. 3 Interfaces: a) bracket interface to backshell and b) TIRS cover interface to bracket (courtesy of JPL).

TIRS cover interface to the backshell, because such a design has never been used on a mission. This report details the results of this SIRCA TIRS cover arcjet test series, which was completed in February 2002.

Arcjet Facilities

Arcjet facilities are used to simulate the aerodynamic heating conditions experienced by spacecraft during atmospheric entry. In general, an arcjet facility uses an electrical discharge to heat a gas stream to a high temperature, resulting in a highly energetic, or high-enthalpy gas flow.[3] This test series was conducted in the NASA ARC 20 MW Panel Test Facility (PTF). The facility consists of a 6-cm-diam constricted arc heater and a convergent–divergent nozzle to provide a dissociated and chemically frozen stream that is expanded into the test chamber. The divergent portion of the nozzle of the PTF has a semi-elliptic shape and yields a supersonic, laminar boundary-layer flow. The air is heated by an electrical arc discharge within a water-cooled constrictor arc column. Heating conditions can be varied by changing the electrical power, reservoir pressure, and the angle of attack of the test panel. Because the test article is not completely isolated from the flow on startup of the facility, it is preheated as the facility stabilizes to the required test condition. The test article is positioned at a negative angle of attack, with respect to the nozzle exit, during the startup to minimize preheating of the test article.

Instrumentation

Two optical pyrometers were used to obtain the local surface temperature of the articles during test. Both pyrometers were mounted on the top of the facility and viewed the top surface of the test articles though windows. The Raytek pyrometer, which operates in the infrared wavelength region, viewed the test articles through a sapphire window (for transmission purposes). This pyrometer has a measurement accuracy of 0.10% (under laboratory conditions with a known emissivity). The second pyrometer, the Mikron M90ZB, which operates in the wavelength range from 8 to 14 μm, viewed the test articles through a zinc–selenide window (for transmission purposes). Uncertainty in the M90ZB pyrometer measurements is $\pm 8^\circ$C (under laboratory conditions with a known emissivity) in the temperature range experienced in this test series.[4] Both pyrometers were set to an emittance of 1.0, which was corrected during posttest data reduction for actual material emissivity and for losses due to transmission through the view windows.

An infrared (IR) camera, set to an emittance of 1.0, viewed the test model surface through a zinc–selenide window, and the readings were corrected for window losses real time. The IR camera is best utilized for evaluation of thermal distribution over the entire test article surface rather than being used for an absolute temperature measurement at a specific location. Therefore, no postprocessing was completed to correct for the actual material emissivity and temperatures. A video camera was mounted on top of the facility to record the events during each test. Pre- and posttest still photographs were also taken of each test model to document the material's appearance.

Standard type-K thermocouples were used to measure the thermal response of the test articles during the exposure and soakback periods. Surface thermocouples were installed on the SIRCA TIRS cover as well as on the backface of the composite structure. In addition, bondline thermocouples (at the interface of the backshell TPS and the composite aeroshell structure) were installed by LMA during the manufacture of the SLA-561S test panel. Thermocouples were also installed on the titanium bracket and in gap locations to evaluate if any hot gas penetration occurred during the test exposure. Thermocouple measurement uncertainty is $\pm 3^\circ$C for the thermocouples used in this test series, considering inherent sensor uncertainty alone.[5] A determination of total experimental error for this test series was not feasible due to project constraints, because this would require tests and analyses involving the effect of the thermocouple sensor on material response and vice versa. A pressure transducer was installed underneath the test article to determine the pressure gradient from the test article surface to the underside during the test exposure.

Test Requirements and Objectives

Although arcjet facilities are the best ground-based test facilities available for atmospheric entry environment simulation, they are not a perfect simulation of the actual flight case into the Martian atmosphere. For example, the test gas is air as opposed to the predominantly carbon dioxide atmosphere of Mars. In addition, spacecraft enter the atmosphere at subzero initial temperatures due to the long cruise in space, as opposed to the 20°C initial temperature for the test case. Consequently, it is not possible to simulate simultaneously all desired parameters of the flight-predicted environment in the test environment. The main objective of this test series was to evaluate the TPS interface, gaps, various seal designs, and exposed hardware in a simulated entry environment, as opposed to obtaining thermal response data and directly comparing the data to design thermal requirements. In addition, a test objective was to bound the peak seal pressure differential of 10 Pa, which was the JPL flight case prediction. To aid in the understanding of some of the differences in the test environment vs the flight environment, pretest analyses were performed to assess the heating and pressure environment for the test case. The arcjet test condition requirements were derived from computational fluid dynamics (CFD) aerothermal analyses of the TIRS cover on the backshell. With use of the NASA Langley Research Center flow code LAURA, LMA performed simplified analyses using a ring geometry, which extruded the TIRS cover geometry all of the way around the spacecraft, as shown in Fig. 4, as opposed to three discrete locations on the backshell. The peak heating on the backshell was found to be highest at a 5-deg angle of attack during entry. Figure 5a shows the predicted streamline traces and Fig. 5b shows the predicted laminar heating profile for flight, based on laminar CFD analyses performed by LMA and two- and three-dimensional CFD analyses performed at NASA ARC. These results verified that the simplified ring geometry was an adequate approximation. NASA ARC used a modified Aerosoft, Inc., GASP code, which has historically compared well with LAURA and the GIANTS (Candler) code, which was used for MPF calculations.

NASA ARC performed SIRCA TPS sizing for the TIRS cover based on the laminar heating environment plus a heating enhancement factor of 2.5 (applied from peak heating to the end of the trajectory) for the possibility of transition to turbulence, plus a 50% aerothermal environment prediction uncertainty factor over the entire trajectory for the base region (an enhancement factor agreed upon by JPL, LMA, and NASA ARC).[6] The resulting peak radiative equilibrium heat flux is 7.5 W/cm^2. The radiative equilibrium total heat load, for the flight case with the enhancement factors listed earlier, is 345 J/cm^2 at the cover apex. For the flight case, recirculating flow is predicted in the region of the TIRS cover; therefore, the peak heating condition occurs on the aft region (or BIP side) of the cover apex (shown in Fig. 5a). Therefore, the arc jet test model had the aft cover region facing the arc jet nozzle exit, that is, the model was mounted backward for the arc jet test.

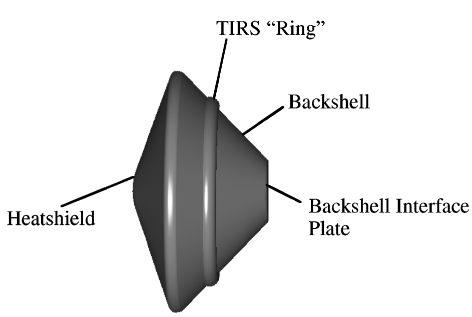


Fig. 4 Simplified ring geometry for TIRS CFD performed by LMA.

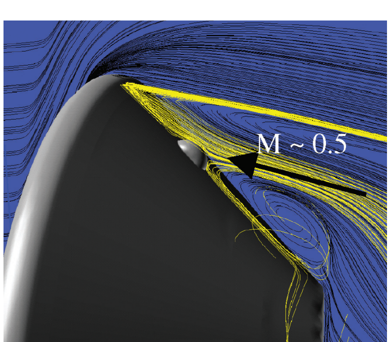


Fig. 5a Predicted streamline traces at the TIRS location.

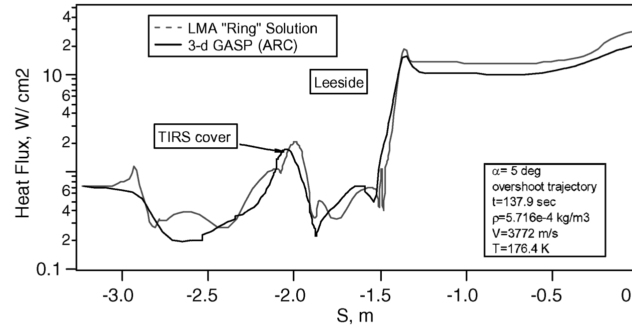
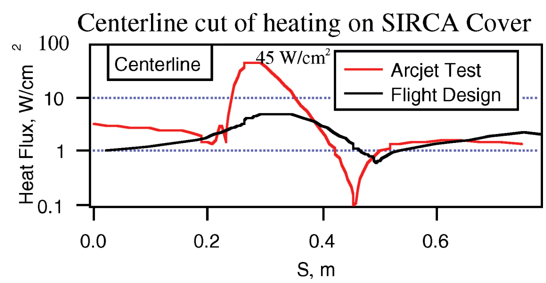
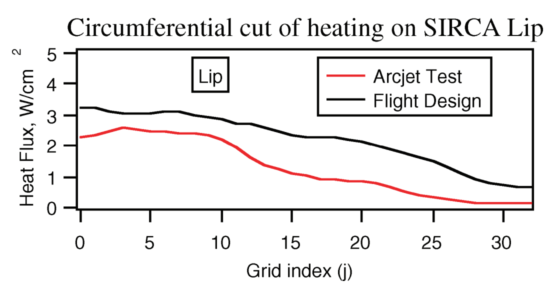


Fig. 5b Laminar aerothermal environment CFD predictions for the TIRS location on the backshell.



a)



b)

Fig. 6 CFD predictions for TIRS cover test article in the PTF at a) TIRS cover centerline and b) lip region.

Pretest Analyses

Pretest CFD analyses were completed by NASA ARC to predict the heating environment on the test model in the PTF at the facility's minimum condition. At this condition, the Mach number in the facility is approximately 4.5, whereas in flight it is predicted to be around 0.5. The higher Mach number was expected to cause a higher heating environment on the TIRS cover in the test as opposed to the flight case. Therefore, the minimum facility condition at a −3-deg table angle of attack (with respect to the arcjet nozzle exit plane) was chosen for the pretest analyses, with the leading edge of the TIRS cover located 16.5 cm from the nozzle exit. Figures 6a and 6b detail the results of these analyses and show that a peak of approximately 45 W/cm^2 was expected on the leading half (or BIP side) of the TIRS cover and that a peak of approximately 2.5 W/cm^2 was predicted on the forward lip region.

Because there is more spatial variation in heat flux for the arcjet test case as opposed to the predicted flight case, it is not possible to simultaneously replicate predicted heating conditions at the cover apex and lip regions in the arc jet test case. The lip region was, therefore, chosen by JPL as the primary location of interest because the exposed bolts and seal were at this location. As seen in Fig. 6b, the resulting test heat flux on the lip region proved to be approximately 17% lower than flight design predictions at the peak location. Although this is a fair representation of flight design predictions for the lip region, this test condition would severely overtest the cover apex by about six times with respect to the predicted flight peak heat flux. Because of concerns of the resulting high thermal gradients (and stresses) in the SIRCA TIRS cover that were not representative of the flight case, and to validate the CFD predictions, a calibration test series was performed in November 2001.

Calibration Test

For the calibration test, a 35.56×35.56 cm SIRCA test panel was manufactured to simulate the curved section of the backshell at the TIRS location and was heavily instrumented with gardon gauge calorimeters and type-K surface thermocouples as shown in Fig. 7. A SILFRAX® insulation test box was manufactured to provide a smooth transition from the nozzle exit and to protect the test article edges. A SIRCA TIRS cover was integrated into the panel and was instrumented with calorimeters (circular foil heat flux transducers), surface thermocouples, and one thermocouple bonded to the inside of the T300 composite facesheet at the apex location to monitor this backface temperature. Small-diameter, uncooled circular foil heat flux gauges were inserted into the bored SIRCA material, so that the surface of the calorimeter was flush with the surrounding SIRCA surface. The surface thermocouples were integrated using a procedure that included a paste to cover the bare thermocouple wire.[7] The paste included an emittance agent to minimize lag in the thermal response. Both the calorimeters and surface thermocouples were used to obtain the heat flux profile on the surface of the TIRS cover. Heat flux values were directly obtained from the calorimeters. Temperatures obtained from the surface thermocouples were used in the SIRCA thermal response model to predict an approximate heat flux value that correlated with the surface temperature response. The TIRS cover longitudinal centerline was assumed an axis of symmetry; therefore, thermocouples were placed near the bolt locations only on one side of the cover. Thermocouples were also placed on the calorimeter bodies to monitor the temperature of the calorimeters, which have an operational temperature limit of 200°C. In addition, a pressure transducer was installed in the test box, below the TIRS cover to ensure a positive pressure differential of at least 10 Pa, which was predicted for the flight case. A positive pressure differential also verifies that this test can adequately evaluate the potential of hot gas penetration through the gaps.

To minimize the preheating on the test article and SIRCA TIRS cover to the greatest extent possible during facility start-up, the test panel angle of attack (with respect to the nozzle exit plane) was −7-deg at the start of the test. Once the facility achieved the required current and voltage (in approximately 40 s), the test panel was brought to −3-deg angle of attack and held for the required test duration. Two test runs were conducted according to Table 1. The termination criterion for the first test was when any calorimeter body reached its operational limit of 200°C.

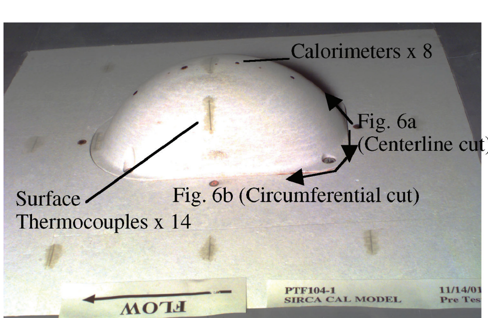


Fig. 7 SIRCA calibration test article (pretest).

Table 1 Calibration test series run sequence, November 2001

Test run	Facility condition current, A; Voltage, V; chamber pressure, kPa	Panel angle of attack, deg	Test time, s	Peak backface temperature, °C[a]
1	1100, 1130, 72	−3	15	96
2	1000, 1100, 72	−3	130	245

[a]Thermocouple sensor uncertainty = ± 3°C.

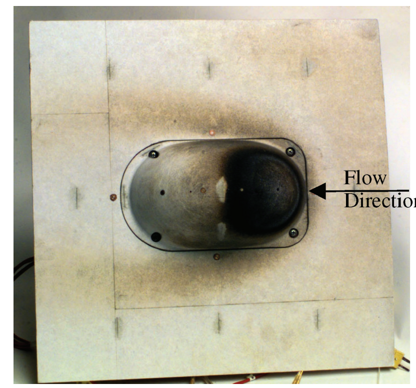


Fig. 8 Calibration test article at posttest.

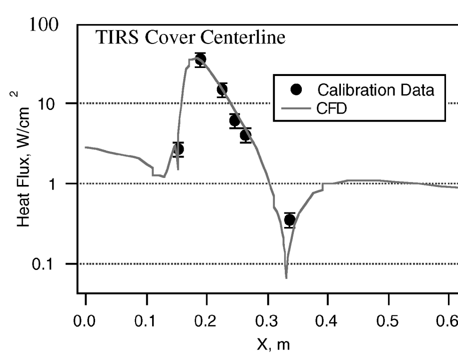


Fig. 9 CFD predictions for SIRCA TIRS cover centerline vs heat flux measurements from calibration run 1.

The second test was conducted to evaluate the test time necessary for the TIRS cover backface to reach a maximum temperature of 250°C, which is the design temperature limit for the silicone adhesive bond between the SIRCA and the composite facesheet. For this second test, it was decided to overheat the calorimeters intentionally and to terminate the test once the backface temperature reached 200°C, with the assumption that the temperature would continue to rise and peak at approximately 250°C during the soak-back period, after the test exposure concluded. The SIRCA charred on the leading-edge portion of the TIRS cover, where the heating rates were the highest, as shown in Fig. 8. Lower heating areas showed either some pyrolysis or remained in the material virgin state (white in color). There is a visible ring toward the outer edge of the charred region, whitish in color, due to the expected oxidation of the charred surface in that region. At the lower heat flux condition at the outer edge of the charred region, the SIRCA did not form a stable char because silicon–oxy carbide was not formed during the conversion of the surface when exposed to the flow.[8] Even though the oxidation is occurring, the underlying surface is still reradiating a significant portion of the imposed energy due to its high emittance (approximately 0.9), and therefore the material remains efficient at dissipating heat.

Figure 9 shows the comparison of the TIRS cover centerline calibration measurements with the CFD predictions, which were refined based on flow characteristic measurements, for example, argon concentration in flow, made during the test. The maximum heating occurred on the leading half (or the BIP side) of the TIRS cover, and the peak heat flux was 37 W/cm^2 (±20%). Note that the apex

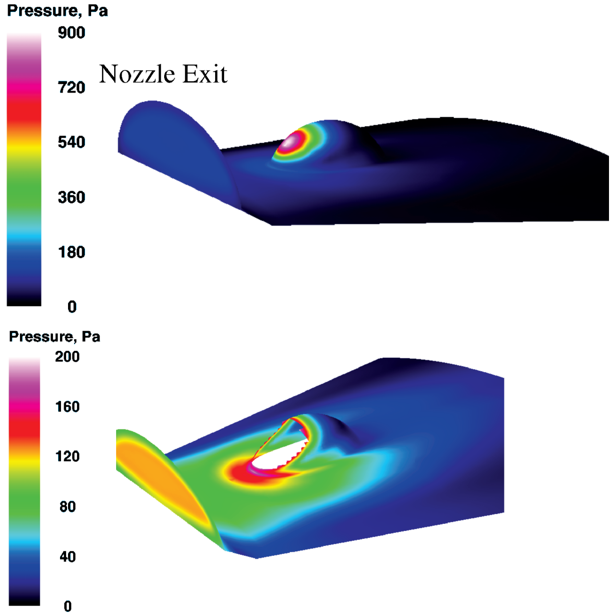


Fig. 10 CFD predictions for surface pressure during test exposure (same data, different scales).

calorimeter (at the $X = 0.2$ m location in Fig. 9) was not perfectly aligned on the longitudinal axis with the peak heating location on the TIRS cover; thus, a slightly lower value was obtained from the calorimeter when compared to the CFD prediction. These results yield confidence in the CFD predictions for the heating distribution on the test article in the PTF and substantiate that the flow remains laminar. Because calibration run 2 overheated the calorimeters, reliable data were not obtained from those instruments, but the surface thermocouple response measured during run 2 was consistent with run 1. Pressure measurements made during the test exposure underneath the test article were approximately 20 Pa. Comparing the pressure measurements with CFD predictions (shown in Fig. 10) verifies there is a positive pressure differential, from the surface to the underside, ranging from approximately 120 to 150 Pa at the leading-edge gap region, and there is very little pressure differential at the aft gap region. There was a positive pressure differential, from the surface to underside, for the majority of the gap region, and the pressure differential meets the minimum requirement of 10 Pa for the majority of locations around the TIRS cover.

The second calibration test was useful in verifying that the resulting high thermal gradients and stresses within the SIRCA and its interface to the composite TIRS cover, under the conditions tested, do not cause any visible cracking in the SIRCA or composite, nor do they cause any evident visual change in the bondline integrity (evaluated through the use of visual inspection and posttest x rays of the TIRS cover). Based on these results, it was decided to pursue arcjet testing of four SIRCA TIRS covers in the flight configuration, including the interface to the SLA-561S backshell TPS and honeycomb structure.

Test Model Design

LMA manufactured four 35.56 by 35.56 cm honeycomb structure panels with the curvature representative of the MER backshell in the location of the TIRS cover. The panels included the flight-representative backshell TPS, SLA-561S, at a nominal thickness of 0.584 cm and were instrumented with thermocouples at various locations at the structure and TPS interface. Four SIRCA TIRS covers were machined and bonded to the composite structure. They were instrumented with thermocouples on the surface and on the backface of the composite structure as shown in Figs. 11a and 11b. Surface thermocouples were installed per the same procedure, and in the same locations, as was the case for the calibration test article. Surface thermocouples were also placed in locations identical to calorimeter locations on the calibration test article. Backface thermocouples were bead-welded and bonded to the backside of the TIRS cover at locations directly opposite the six surface thermocouples distributed along the centerline and on one off-center location. Two flight-representative titanium brackets were provided by JPL and were heavily instrumented with thermocouples. Additional bead-welded thermocouples were installed on the backshell panel to monitor the structure at various locations, including the critical bracket and aeroshell interface.

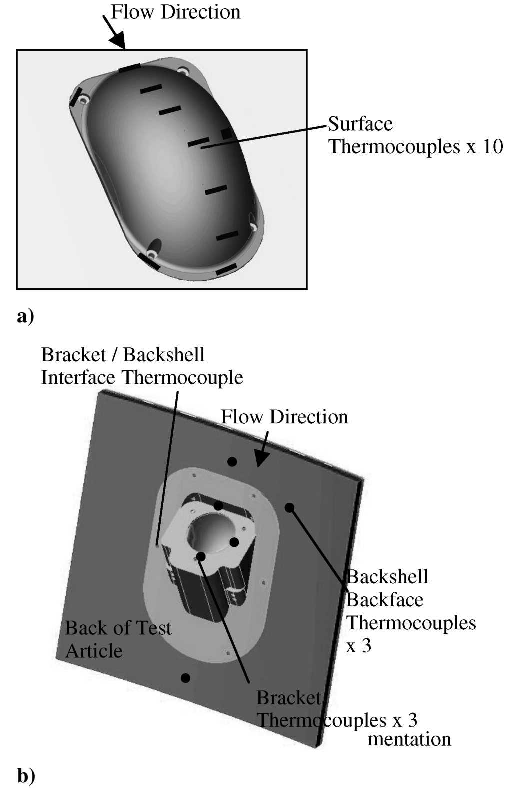


Fig. 11 Thermocouples: a) TIRS cover and b) bracket instrumentation (courtesy of JPL).

Because four test models were manufactured, JPL intended to test various seal configurations in the test series. The first test would be the baseline seal design, that is, the Nextel rope and silicone seal installed between the bracket and backshell structure. If the baseline seal design was successful in preventing hot gas penetration, the second test would consist of the Nextel rope only, without any silicone seal. If that seal was successful in preventing hot gas penetration, the third test would consist of an open gap, that is no Nextel rope or silicone seal. Whereas the baseline design includes the Nextel rope and silicone seal, the other test configurations were designed to obtain data for unexpected situations where parts of the seal are missing, for example, damage during installation or during flight. The fourth test model was tested with the Nextel rope and no silicone seal to obtain a duplicate set of data for the second configuration.

Test Condition

Table 2 summarizes the test matrix for this test series. All test articles were tested to identical heating conditions to evaluate the resulting performance of the different seal designs. The test duration was selected to match the predicted peak flight heat load at the critical lip region, which consequently results in a heat load eight times greater for the TIRS cover apex than that predicted for the flight case.

Test Results and Discussion

Table 3 summarizes the material surface thermal response and selected thermocouple response at critical interface locations. The following discussion details the test article configuration, thermal response, and posttest inspection results.

Table 2 TIRS cover arcjet test matrix, February 2002

Model identification	Cold wall apex peak test heat flux,[a] W/cm^2	Cold wall peak lip region heat flux,[a] W/cm^2	Test time, s	Total apex peak heat load, J/cm^2	Total lip region peak heat load, J/cm^2
MERTIRS-0202-A	37	2.5	74	2738	185
MERTIRS-0202-B	37	2.5	74	2738	185
MERTIRS-0202-C	37	2.5	74	2738	185
MERTIRS-0202-D	37	2.5	74	2738	185

[a]Values from CFD predictions.

Table 3 Material surface thermal response and summary of selected thermocouple peak temperatures at critical interface locations

Model identification	Seal	Peak SIRCA surface temperature,[a] °C	Peak SLA-561S surface temperature,[b] °C	Bracket and aeroshell interface peak temperature,[b] °C	TIRS cover and bracket interface peak temperature,[b] °C	TIRS cover backface peak temperature,[b] °C
MERTIRS-0202-A	Nextel plus adhesive	1063	492	61	70	246
MERTIRS-0202-B	Nextel only	1053	490	61	63	Not operational
MERTIRS-0202-C	No seal	1057	491	58	62	232
MERTIRS-0202-D	Nextel only	1032	406	54	60	222

[a]Pyrometer aligned to approximate peak heating location on dome section of TIRS cover. [b]Thermocouple sensor uncertainty of ±3°C.

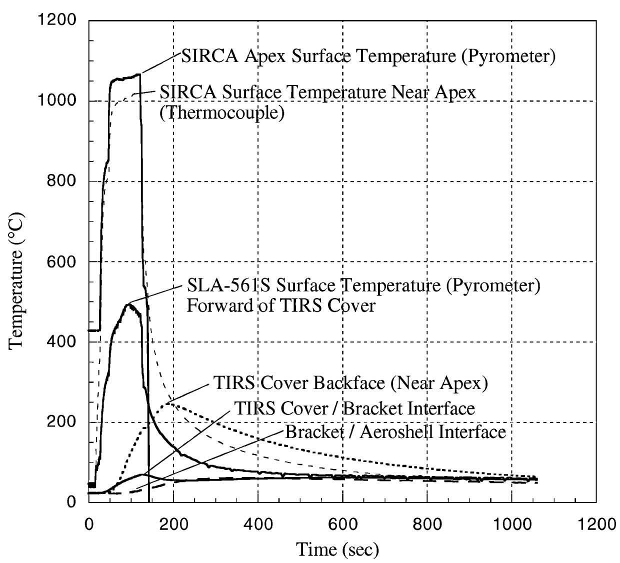


Fig. 12 Thermal response of test article MERTIRS-0202-A.

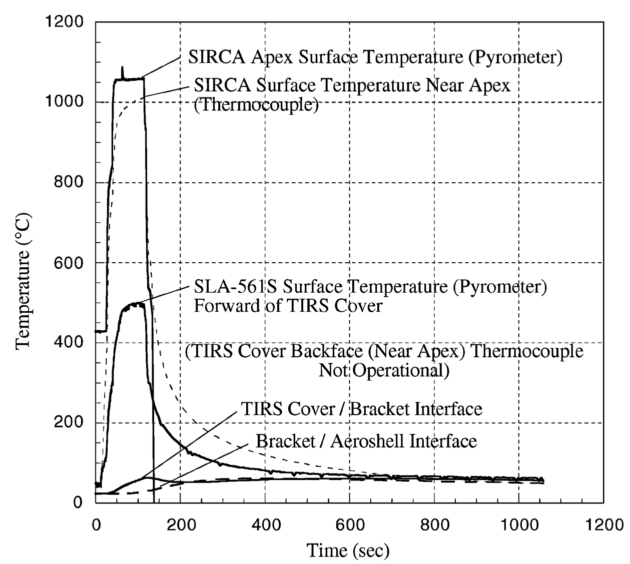


Fig. 13 Thermal response of test article MERTIRS-0202-B.

Test Article MERTIRS-0202-A

Test model MERTIRS-0202-A was configured with the baseline seal design between the bracket and backshell structure, that is, Nextel rope around the gap perimeter and a silicone adhesive placed on top of the rope seal. One pyrometer was aligned to record the surface temperature of the SLA-561S material just forward of the TIRS cover, and the second pyrometer was aligned to record the surface temperature of the SIRCA TIRS cover apex.

Selected pyrometer and thermocouple response is shown in Fig. 12. The surface temperature at the SIRCA TIRS cover apex peaked at 1063°C, and the cover backface thermocouple peaked at 246°C. Visual posttest inspection of the SIRCA TIRS cover showed a charred surface at the peak heating location on the cover, consistent with the calibration test article. The remaining surface area of the material remained in essentially the virgin state (white in color). Posttest weight measurements of the SIRCA TIRS cover showed a mass loss of 0.41 g, which amounts to 0.2% of the pretest system weight. Under this test condition, minimal pyrolysis of the silicone occurred during the formation of the surface conversion layer. The surface temperature of the SLA-561S, just forward of the TIRS cover, peaked at 492°C. At the TIRS cover and bracket interface (at the leading edge, closest to the nozzle exit), the thermocouple peaked at 70°C, and at the bracket and aeroshell interface location, the thermocouple peaked at 61°C.

At posttest, the TIRS cover was carefully disassembled, and the seal area was inspected. The silicone seal was still red in color and showed no evidence of overheating. The exposed bolts at the leading edge location showed slight oxidation and surface peeling, but showed no sign of melting. Based on a visual inspection, there was no evidence of overheating of the seal, bracket, or backshell honeycomb structure. In addition, posttest measurements were made of the gap width between the SIRCA lip region and the neighboring SLA-561S, and there was no change in gap widths from the pretest measurements. The successful results yielded confidence in the baseline seal design.

Test Article MERTIRS-0202-B

This test article was configured with the Nextel rope without any silicone seal in the gap. A new instrumented SIRCA TIRS cover was used for this test, and the pyrometers were aligned identical to the preceding test article.

The surface temperature and selected thermocouple response is shown in Fig. 13. The surface temperature at the TIRS cover apex was consistent with the preceding test article and peaked at 1053°C.

The TIRS cover backface thermocouple at the apex location was not operational and did not return any data. The posttest visual appearance of the SIRCA TIRS cover was consistent with the preceding test article. A weight loss of 0.38 g, or 0.2% of the pretest weight, was calculated from posttest weight measurements of the TIRS cover. The surface temperature of the SLA-561S, at the forward location, peaked at 490°C, and the surface appearance showed minimal change from pretest. At the TIRS cover and bracket interface (at the leading edge, closest to the nozzle exit), the thermocouple peaked at 63°C, and at the bracket and aeroshell interface location, the thermocouple peaked at 61°C.

The TIRS cover was removed to allow for inspection of the Nextel rope seal. There was some yellowish discoloration on the rope seal (and adjacent SLA-561S material) at the leading-edge and just aft of the leading-edge corner locations, most likely due to pyrolysis products from the decomposition of the SIRCA material. This is a second confirmation that a pressure differential existed such that the flow would travel from the surface into the gap. Posttest visual appearance of all other hardware was consistent with the preceding test article, and there was no evidence of overheating, hot gas penetration through the rope seal, or gap width change.

Test Article MERTIRS-0202-C

This test article was configured without any rope or silicone seal to evaluate the effect of hot gas ingestion into the gap. The pyrometers were aligned to the SLA-561S surface and the SIRCA TIRS cover apex, just as was the case for the two preceding test articles.

Figure 14 shows the thermal response for this test article. The SIRCA surface temperature was consistent with the preceding test articles and peaked at 1057°C. The TIRS cover backface thermocouple peaked at 232°C. The posttest appearance of the SIRCA TIRS cover was consistent with the preceding test articles and a weight loss of 0.23 g, or 0.12% of the pretest TIRS cover weight, was calculated from posttest weight measurements. The surface temperature of the SLA-561S, at the forward location, peaked at 491°C. At the TIRS cover and bracket interface (at the leading edge, closest to the nozzle exit), the thermocouple peaked at 62°C, and at the bracket and aeroshell interface location, the thermocouple peaked at 58°C.

The TIRS cover was disassembled for inspection of the test article and bracket interface without any seal. Consistent with the preceding test articles, there is discoloration on the SLA-561S material most likely due to SIRCA decomposition products. There was no visual evidence of overheating or damage to the honeycomb composite structure; therefore, it appears that even without a seal of any kind, the bracket interface design protects the backshell structure from hot gas exposure under these test conditions.

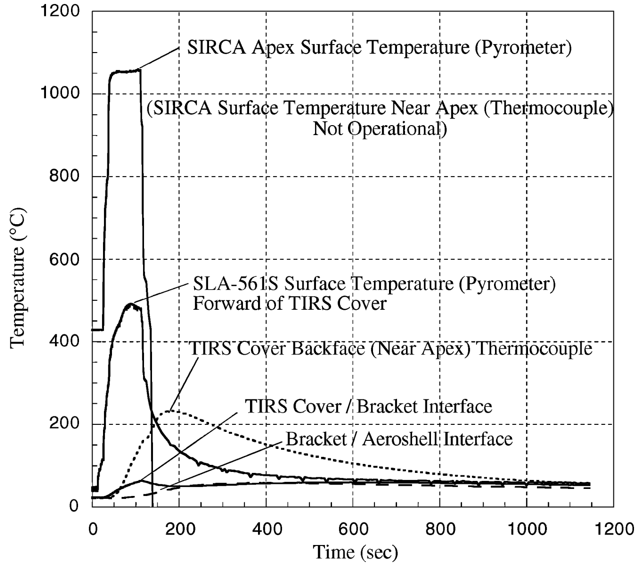


Fig. 14 Thermal response of test article MERTIRS-0202-C.

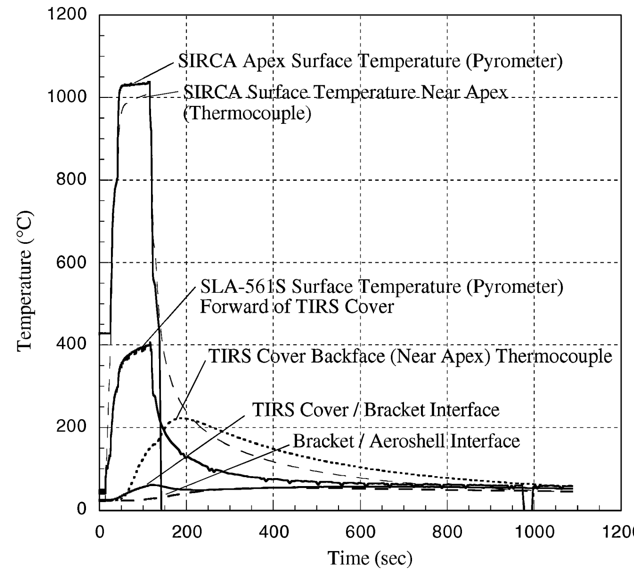


Fig. 15 Thermal response of test article MERTIRS-0202-D.

Test Article MERTIRS-0202-D

To obtain a duplicate set of data for the second seal configuration, this test article was configured with the Nextel rope without any silicone seal in the gap. Figure 15 shows the thermal response for this test article. The surface temperature at the SIRCA TIRS cover apex peaked lower than preceding test articles at 1032°C, and the cover backface thermocouple peaked at 222°C. Posttest visual appearance of the TIRS cover was consistent with preceding test articles and a weight loss of 0.20 g, or 0.10% of the pretest TIRS cover weight, was calculated from posttest weight measurements. The surface temperature of the SLA-561S, at the forward location, peaked at 406°C. At the TIRS cover and bracket interface (at the leading edge, closest to the nozzle exit), the thermocouple peaked at 60°C, and at the bracket and aeroshell interface location, the thermocouple peaked at 54°C. In general, the thermal response of all thermocouples for this model were lower than preceding test articles. After evaluation of the facility parameter data, it appears that a slight facility variance (lower voltage) created a more benign environment than the preceding three test articles.

The TIRS cover was removed for posttest inspection of the Nextel rope seal. There were some decomposition products deposited on the bracket edges and underneath the TIRS cover at the leading-edge location, but the Nextel rope seal remained in excellent condition.

Thermal Response Predictions

One-dimensional SIRCA thermal response predictions were performed for two locations and were compared with thermocouple data. The first location for SIRCA thermal response prediction comparisons was the leading edge lip section of the TIRS cover at the bolt location, and Fig. 16 shows these results. Data from the thermocouple at the TIRS cover and bracket interface for each test article shows good repeatability in response, with a maximum temperature differential of 3%. SIRCA thermal response predictions were performed according to a nominal SIRCA material thickness (0.35 cm) based on JPL design drawings. Because there was as much as a 20°C disparity between this prediction and the thermocouple data, the test articles were physically measured in this location. It was found that the SIRCA thickness at this location for the test articles was thinner than the nominal design thickness. It was also discovered that the bonding and integration procedure for the SIRCA onto the composite covers allows for the SIRCA thickness in this region to vary. During the integration process, the SIRCA, adhesive, and structure total thickness is held constant, so that if higher than nominal adhesive thickness is used, the resulting SIRCA thickness becomes less than the nominal design thickness. The average SIRCA thickness in this lip region for the test articles was measured to be 0.254 cm, and so a new prediction was performed with this SIRCA thickness.

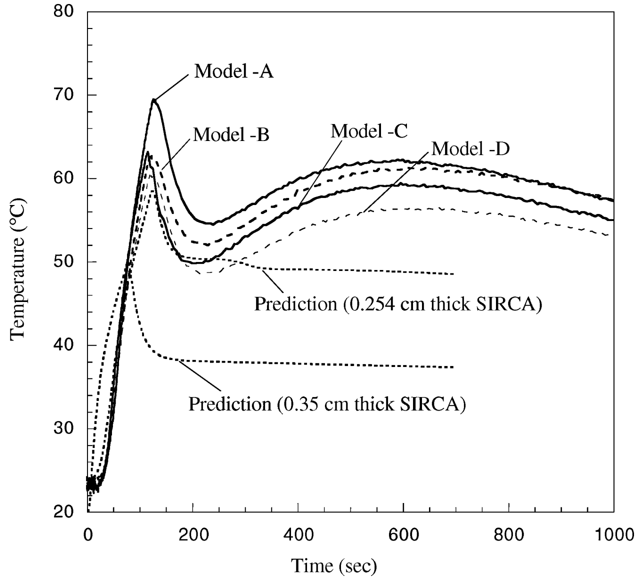


Fig. 16 SIRCA thermal response predictions vs thermocouple data for the lip region at the bolt location.

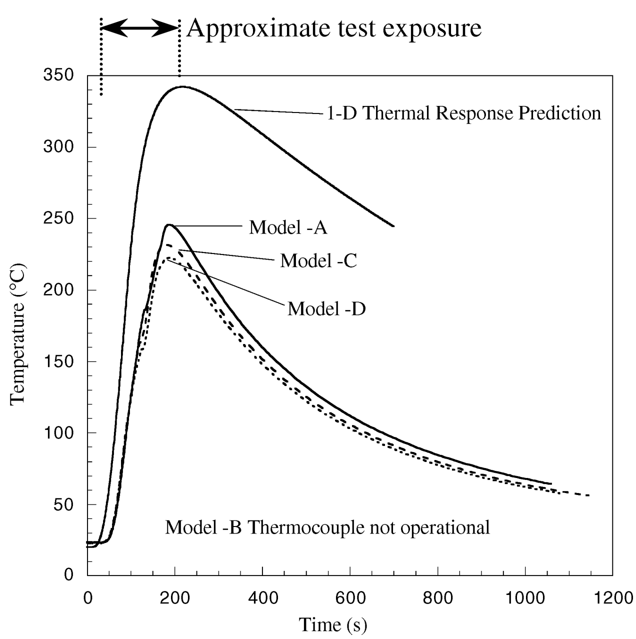


Fig. 17 SIRCA thermal response predictions vs thermocouple data at the TIRS cover backface peak heating location.

The resulting predicted response for the thinner SIRCA case proved to be a much better match to the thermocouple data for the initial peak that occurs during the test exposure. The prediction compared to within 7% of the averaged thermocouple data for the initial temperature peak during the test exposure. The second peak is not predicted because only a one-dimensional analysis was performed, which does not account for multidimensional conduction effects during the soak-back period. At this location, a one-dimensional analysis proved to be a good approximation of the thermal response during the test exposure in which multidimensional conduction effects do not predominate. Conversely, multidimensional effects are predominant for the duration after the test exposure has concluded. Because the peak temperature occurs during the test exposure, the second peak is not the primary thermal driving requirement. The minimum SIRCA thickness in this region was calculated to be 0.127 cm to meet the thermal insulation requirements.[2] The nominal design thickness of 0.35 cm allowed for a flush transition from the SIRCA to the neighboring aeroshell TPS, SLA-561S, and is, therefore, conservative with respect to thermal insulation. It was recommended to JPL that the SIRCA thickness in this region be at least 0.127 cm to meet the thermal insulation requirements based on the TPS sizing exercise performed by NASA ARC.

The second location for SIRCA thermal response predictions was the TIRS cover backface at the approximate peak heating location. Figure 17 shows the predictions vs the thermocouple data for test articles that had an operable backface thermocouple. Figure 17 shows good repeatability in thermocouple response with a maximum temperature differential of approximately 5%. For this case, the one-dimensional assumption in the thermal response prediction yielded results that were significantly higher than the thermocouple data. A multidimensional analysis was not performed due to project constraints and the resulting conservative one-dimensional analysis. This highlights that the SIRCA thermal response at the dome section of the TIRS cover is highly multidimensional due to its geometry.

Conclusions

Four SIRCA TIRS covers were tested in an arcjet environment with two different seal configurations and one case without any seal. The SIRCA TIRS covers were integrated into a test panel that included a flightlike configuration of the backshell TPS, SLA-561S. The test condition was designed to match the predicted peak flight heat load at the gap region between the SIRCA and the backshell TPS material. The resulting test heat flux on the lip region was shown to be approximately 17% lower than flight design predictions at the peak lip heating location. Although this was a fair representation of flight design predictions for the lip region, this test condition severely overtested the cover apex by about six times with respect to the predicted flight peak heat flux. Calibration tests with a SIRCA TIRS cover were performed to validate the CFD predictions and to ensure that the resulting high thermal gradients and stresses, within the SIRCA and its interface to the composite TIRS cover, do not cause any visible cracking in the SIRCA or composite. This result was verified, and there was no observable visual change in the bondline integrity. For the SIRCA TIRS test articles, the pressure differential was as much as 20 times the minimum requirement of 10 Pa, depending on the location. For all test articles, regardless of seal configuration, there was no visual evidence of overheating or damage to the seal (if applicable), bracket, or backshell structure. The exposed titanium bolts were in good condition at posttest and showed only a small amount of oxidation at the leading-edge locations.

Repeatable thermocouple data were obtained, and SIRCA thermal response analyses were compared to applicable thermocouple data. The one-dimensional thermal response prediction compared to within 7% of the averaged thermocouple data for the initial temperature peak during the test exposure for the leading-edge lip region at the bolt location, once an accurate thickness of SIRCA material was determined. It was recommended to JPL that, during the SIRCA machining process, the thickness for the lip region be at least 0.127 cm to meet the JPL-defined thermal insulation requirements. For the apex region of the SIRCA TIRS cover, the one-dimensional thermal model overpredicted the peak backface temperature because there were strong multidimensional conduction effects due to the geometry of the TIRS cover. This result highlights that a one-dimensional TPS sizing analysis for the TIRS cover apex is conservative. In general, the test results provide strong experimental evidence that supports the adequacy of the baseline seal design. Based on these test results, JPL proceeded with the baseline seal design for the flight hardware integration onto the aeroshell.

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References

[1]Szalai, C., Chen, Y.-K., Loomis, M., Hui, F., and Scrivens, L., "Mars Exploration Rover Silicone Impregnated Reusable Ceramic Ablator Backshell Interface Plate Testing in the NASA Ames Panel Test Facility," NASA Ames Research Center Document Control Center, No. A9SP-0004-XV403, Oct. 2002.

[2]Szalai, C., Chen, Y.-K., Loomis, M., and Tauber, M., "Mars Exploration Rover Silicone Impregnated Reusable Ceramic Ablator Thermal Response Analysis Summary," NASA Ames Research Center Document Control Center, No. A9SP-0004-XD250, Oct. 2002.

[3]Balter-Peterson, A., Nichols, F., Mifsud, B., and Love, W., "Arc Jet Testing in NASA Ames Research Center Thermophysics Facilities," AIAA Paper 92-5041, Dec. 1992.

[4]*Mikron Infrared Thermometer Owner's Manual*, Mikron Instrument Co., Wyckoff, NJ, 1990.

[5]*Manual on the Use of Thermocouples in Temperature Measurement*, 4th ed., ASTM Manual Series MNL 12, American Society for Testing and Materials, Philadelphia, 1993, Chap. 3.2.2, p. 54.

[6]Loomis, M., "ARC 2.5 Turbulence Factor Rationale Documentation for MER," Space Technology Div., NASA Ames Research Center, Moffett Field, CA, Oct. 2001.

[7]"Work Instructions for Thermocouple Installation in a SIRCA Tile," NASA Ames Research Center Document Control Center, No. A9FP-9703-XR212, 1998.

[8]Tran, H., Johnson, C., Rasky, D., and Hui, F., "Silicone Impregnated Reusable Ceramic Ablators for Mars Follow-On Missions," AIAA Paper 96-1819, June 1996.

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